

# *uvby* – $\beta$ PHOTOELECTRIC PHOTOMETRY OF CEPHEID STARS<sup>1</sup>

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## RESUMEN

Presentamos fotometría fotoeléctrica *uvby*– $\beta$  de 41 estrellas Cefeidas clásicas. Una breve discusión de los datos comparados con observaciones análogas se ha llevado a cabo

## ABSTRACT

We present time-series *uvby* –  $\beta$  photometry of 41 classical Cepheid stars. A brief discussion of the comparison between the presented data and previous photometric data has been done.

**Key Words:** **PHOTOMETRY - STRÖMGREN PHOTOMETRY - STARS - CEPHEID STARS**

## 1. INTRODUCTION

The relevance of classical Cepheids in stellar astrophysics, both as distance indicators and in understanding stellar structure and pulsation, has been long acknowledged. The Strömgren (*uvby* –  $\beta$ ) photometric system has proven to be very useful in the determination of fundamental physical quantities such as reddening, effective temperature, gravity and metallicity, for main sequence (Crawford 1975), giant (Olsen 1984) and supergiant stars (Arellano Ferro & Parrao 1990; Arellano Ferro & Mantegazza 1996). Large compilations of *uvby* –  $\beta$  photometry of Cepheids have been published in the past (Feltz & McNamara 1980; Eggen 1983, 1985; Meakes et al. 1991; Arellano Ferro et al. 1998). However, while there are some intersections in the stars studied in these works, there are many poorly observed Cepheids. In this paper we present new *uvby* –  $\beta$  data for 41 Cepheids, many of which have very little or no previous Strömgren photometry.

## 2. OBSERVATIONS

The observational data were gathered during different seasons (see Table 1) at the San Pedro Mártir Observatory, in Baja California, Mexico. All the data was obtained at the 1.5 m telescope to which a six-channel grating spectrophotometer was attached. In most of the seasons the observational procedure was the same; each data point reported is the average of at least five 10 s integrations and both sets of *uvby* data and the narrow and wide bands that define the  $\beta$  index were observed almost simultaneously. A single measurement of the sky with an integration time of 10 s was subtracted from the star measurements. On each night several standard stars were observed to carry out the transformation into the standard system of Olsen (1983) and Crawford (1975; 1979). The reduction procedure was done with NABAPHOT package (Arellano Ferro & Parrao 1989) that corrects for atmospheric extinction, transforms the data into the standard system and converts the sidereal time into Heliocentric Julian Day. The standard stars were taken from Grönbech & Olsen (1976; 1977) and Olsen (1983), but some of the bright standard stars were taken from the list published in the Astronomical Nautical Almanac.

The transformation equations used in the work have the following forms:

$$\begin{aligned} V &= A + B (b - y)(\text{inst}) + y (\text{inst}) \\ (b - y) (\text{std}) &= C + D (b - y)(\text{inst}) \\ m_1(\text{std}) &= E + F m_1(\text{inst}) + J (b - y)(\text{inst}) \end{aligned}$$

<sup>1</sup>Based on observations collected at the San Pedro Mártir Observatory, Mexico.

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TABLE 1  
LOG OF THE OBSERVING SEASONS.

Epoch	No of stars	Initial date	Final date	observers
		year mo day	year mo day	
1989 OctNov	16	1989 10 29	1989 11 07	jhp, rpg
2005 MayJune	4	2005 05 28	2005 06 31	jhp, rpm
2006 July	7	2006 07 14	2006 07 19	ma, jps
2006 November	12	2006 11 01	2006 11 13	ma, lpl, jps, yr
2006 December	8	2006 12 09	2006 12 11	jhp, jps, hg
2007 MarchApril	8	2007 03 30	2007 04 03	jhp, gm, bv
2007 October	12	2007 10 05	2007 10 26	jhp, jps, cg
2008 October	8	2008 10 08	2008 10 14	ma, jps
2008 December	9	2008 12 09	2008 12 14	jhp, pz, vha
2009 June	9	2009 06 24	2009 06 26	jhp, hg, arl

jhp, J.H. Peña; rpg, R. Peniche; rpm, R. Peña Miller; jps, J. P. Sareyan; ma, M. Alvarez; yr, Y. Rosas; lpl, L. Parrao; hg, H. Garcia; gm, G. Muñoz; bv, B. Vargas; cg, C. Guerrero; pz, P. Zasche; vah, V. H. Alvarado and arl, A. Renteria

$$c_1(\text{std}) = G + H c_1(\text{inst}) + I (b - y)(\text{inst})$$

$$\beta(\text{std}) = K + L \beta(\text{inst}).$$

In Fig. 1 the transformations between the instrumental and the standard values for a group of standard stars for the night of October 11, 2008 are illustrated. Table 2 presents the values of the slopes and color term coefficients averaged for seven nights from the 2008 season. Standard deviations for each coefficient are at the bottom of this table. Except for the May 2005 season, which was devoted entirely to the data acquisition of Cepheid stars, most seasons were planned for the observations of short period variable stars and hence few data points of Cepheid and standard stars were obtained on each night. Nevertheless, some seasons were long enough to obtain data strings suitable for the long periods of some Cepheid stars.

### 2.1. Photometric uncertainties

Individual uncertainties were determined by calculating the standard deviations of the fluxes in each filter for each star. It is obvious that the brighter stars were more accurately observed than the fainter ones. However, the faint stars were observed long enough to secure sufficient photon counting to get high S/N ratios. Representative values of the photon counting errors  $N/\sqrt{N}$  derived from the measurements on the night of October 11, 2008 for Cepheids with magnitudes  $V$  from 5.2 to 11.6 are listed in Table 3. The standard star BS 1430 was included for comparison. In view of the results, errors associated

with photon counting appear negligible.

Season errors were evaluated through the differences (calculated minus reported) of the magnitude and colors for the standard stars. Ten to fifteen standard stars were observed on each night. Emphasis is made on the large range in the magnitude and color values of the standard stars (see Fig. 1). We present the standard deviations of the mean values of these differences  $\langle \delta(V, (b - y), m_1, c_1) \rangle = (0.012, 0.005, 0.007, 0.018)$  for the October 2008 season.

## 3. RESULTS

A log of the observations is given in Table 4. Column 1 gives the star name; columns two and three, the ephemerides elements employed to calculate the phase in the light curves. These elements were taken from the General Catalogue of Variable Stars (Samus et al. 2010) which provides correct phase light curves. Subsequent columns in the Table report the number of observations for each star by each one of the previously mentioned authors who provided  $uvby - \beta$  photometry, namely, Feltz & McNamara (1980), Eggen (1983, 1985), Meakes et al. (1991) and Arellano Ferro et al. (1998). The last column lists the number of observations the present paper provides. The magnitudes and colors obtained in the present paper in the standard system for our sample of Cepheids are listed in Table 5 which is available only in electronic form. A small portion of this Table is illustrated as Table 5 in the printed version.

TABLE 2

MEAN VALUES AND STANDARD DEVIATIONS  $\langle \sigma \rangle$  OF THE TRANSFORMATION COEFFICIENTS OBTAINED FOR THE OCTOBER, 2008 SEASON

season	B	D	F	J	H	I	L
2008	0.884	0.996	1.027	0.013	1.007	0.062	-1.319
$\langle \sigma \rangle$	0.026	0.015	0.081	0.031	0.054	0.074	0.065

TABLE 3

PHOTON COUNTING ERRORS ON THE NIGHT OF  $OCT11^{TH}$ , 2008

ID	V	$u$	$b$	$v$	$y$	N
BS 1430	5.4	0.0004	0.0003	0.0002	0.0003	4
RT AUR	5.2	0.0005	0.0003	0.0002	0.0003	5
SZ TAU	6.5	0.0009	0.0006	0.0004	0.0004	6
ST TAU	8.5	0.0023	0.0014	0.0010	0.0010	6
SY AUR	9.0	0.0040	0.0020	0.0020	0.0020	6
AO AUR	9.1	0.0023	0.0014	0.0010	0.0010	10
AN AUR	10.7	0.0070	0.0040	0.0020	0.0020	10
ER AUR	11.6	0.0090	0.0050	0.0030	0.0030	10

#### 4. COMPARISON WITH OTHER PHOTOMETRIES

The confidence level of our reported values should be judged through the discussed uncertainties. Goodness of the quality of our data can be demonstrated through the agreement with the previously reported  $uvby - \beta$  observations. These sources were mentioned before and the number of data points for each star is listed in Table 4. We have chosen four stars with a large number of observations from different authors to demonstrate this point of agreement among these observations. The stars considered for the comparison were X Cyg, VZ Cyg, SW Tau and SS Tau. As can be seen in Figure 2 they are all in perfect agreement. The comparison between the data of Arellano Ferro et al. (1998) and those of the present paper was done for all the stars and all the observations fit either in the light curve and color index diagrams demonstrating once again the stability of the stars and the quality of the observations. Figures 3 to 5 show the light curves for most of the Cepheids in our sample. In these Figures we have included two data sets for each star, namely Arellano Ferro et al. (1998), represented by open circles, and those of the present paper, filled circles.

#### 5. CONCLUSIONS

New  $uvby - \beta$  photoelectric photometry has been acquired and is presented for 41 Cepheid stars. We

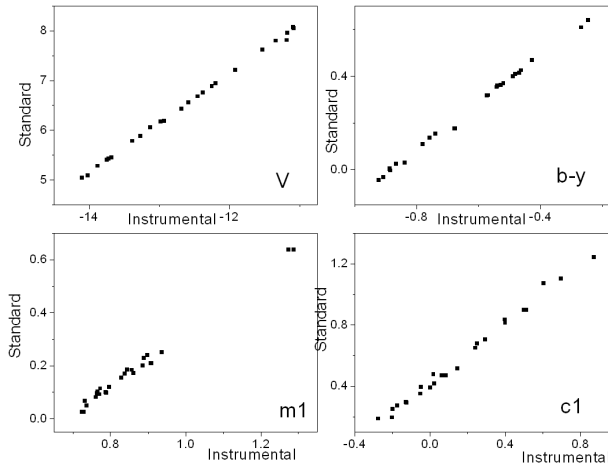


Fig. 1. Sample of the transformation correlations between instrumental and standard values for a groups of standard stars for the October, 2008 season

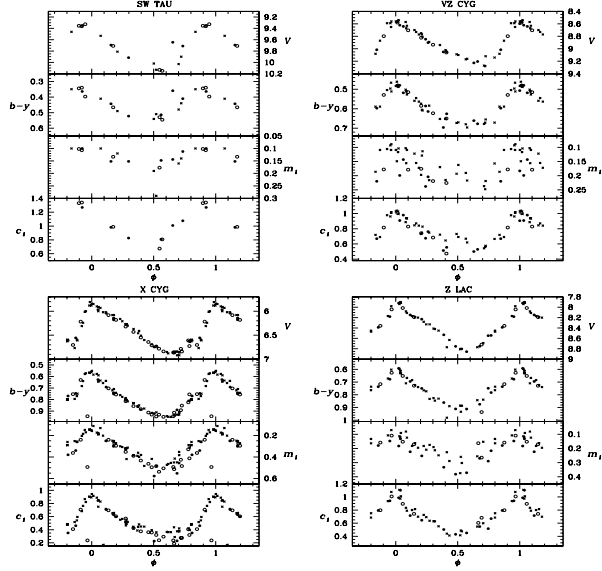


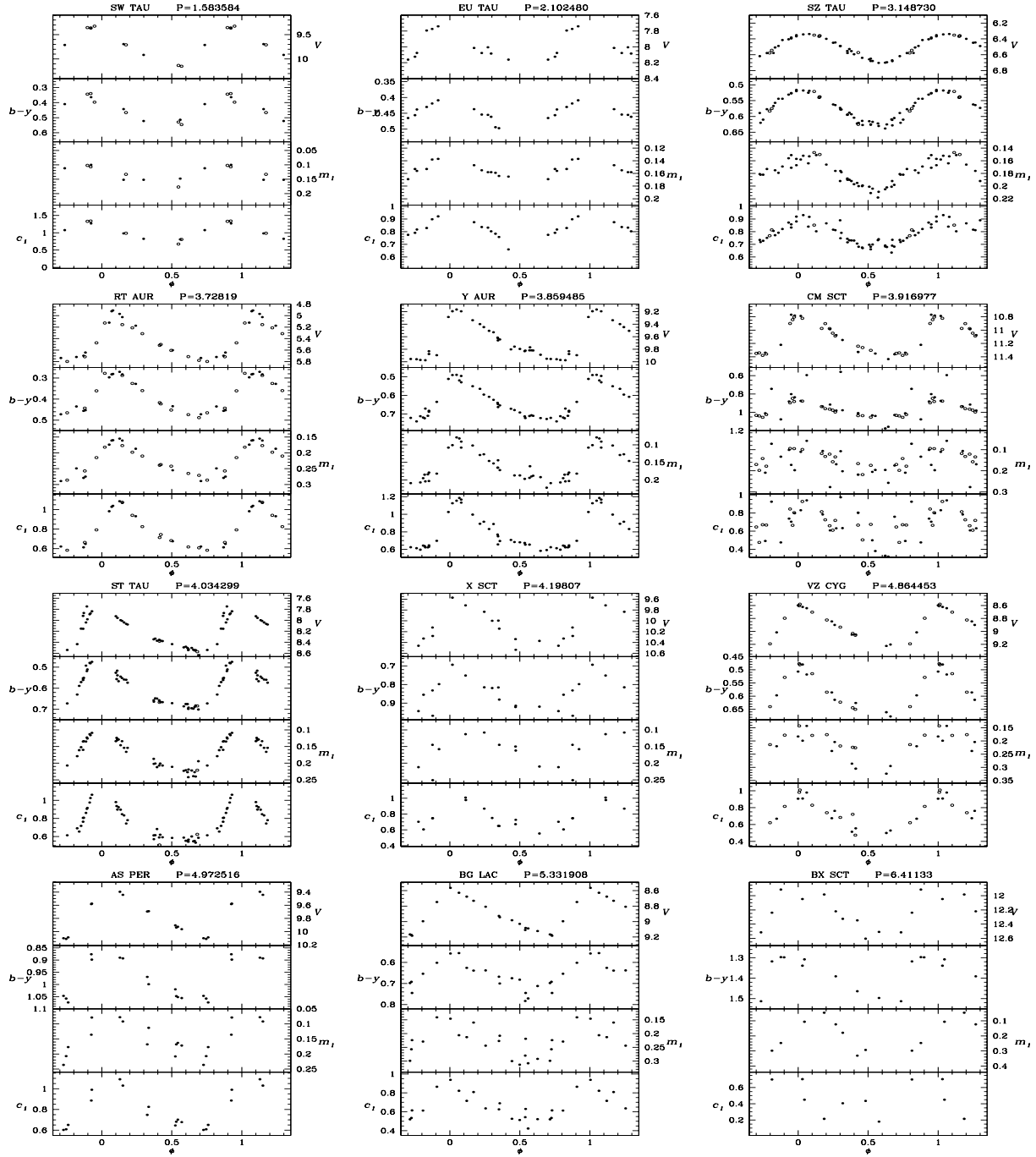
Fig. 2. Light curves in  $uvby - \beta$  for four stars observed by several authors. The agreement between the sources shows the several data sets is good. Open circles: Arelano Ferro et al. (1998); crosses, Feltz & McNamara (1980); filled circles, present work

trust that  $uvby - \beta$  data, like that presented in this work, may be useful on other fronts of Cepheid research such as secular period changes (Szabados 1991; Arelano Ferro 1983), metallicity (Arelano Ferro & Mantegazza 1996), reddening (Chulhee 2008) and other physical parameter determinations, for instance the radii through the Baade-Wesseling approach (Arelano Ferro & Rosenzweig 2000). This photometry can also be utilized to reach several other goals: to establish a relationship with the physical properties such as the empirical determinations developed in RR Lyrae stars (e.g. Kovács and Walker 2001 and references within) through a Fourier decomposition of the light curves (e.g. Peña et al. 2009); to determine the metallicity photometrically from the color indexes compared directly to the theoretical models (e.g. Meakes, Wallerstein & Fuller Opalko 1991); to support and improve knowledge of the chemical enrichment gradient in the galaxy (e.g. the series of papers by Andrievsky et al. 2004 and references within) among other topics.

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Fig. 3.  $uvby - \beta$  Light curves of sample Cepheids

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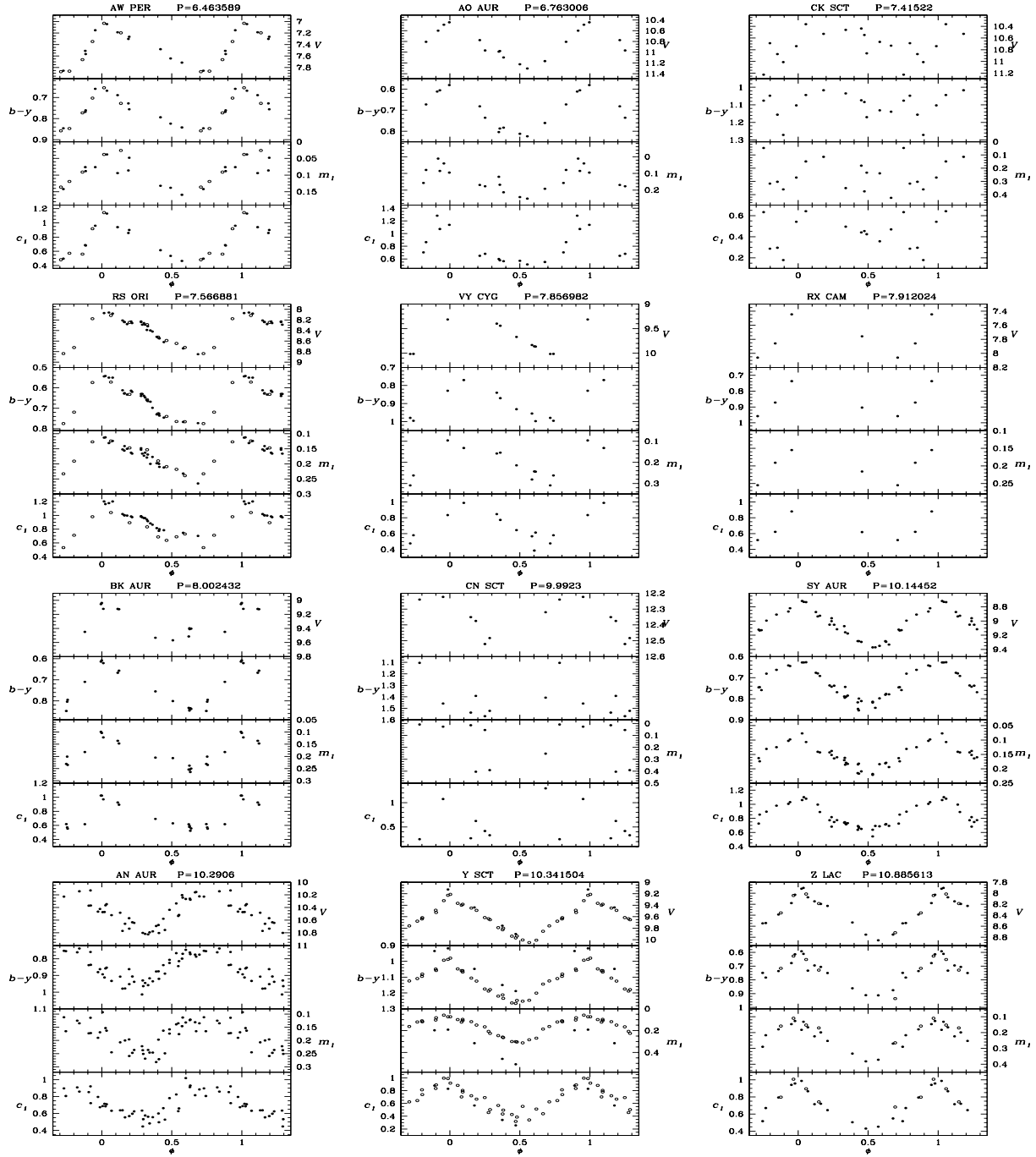


Fig. 4. Continue

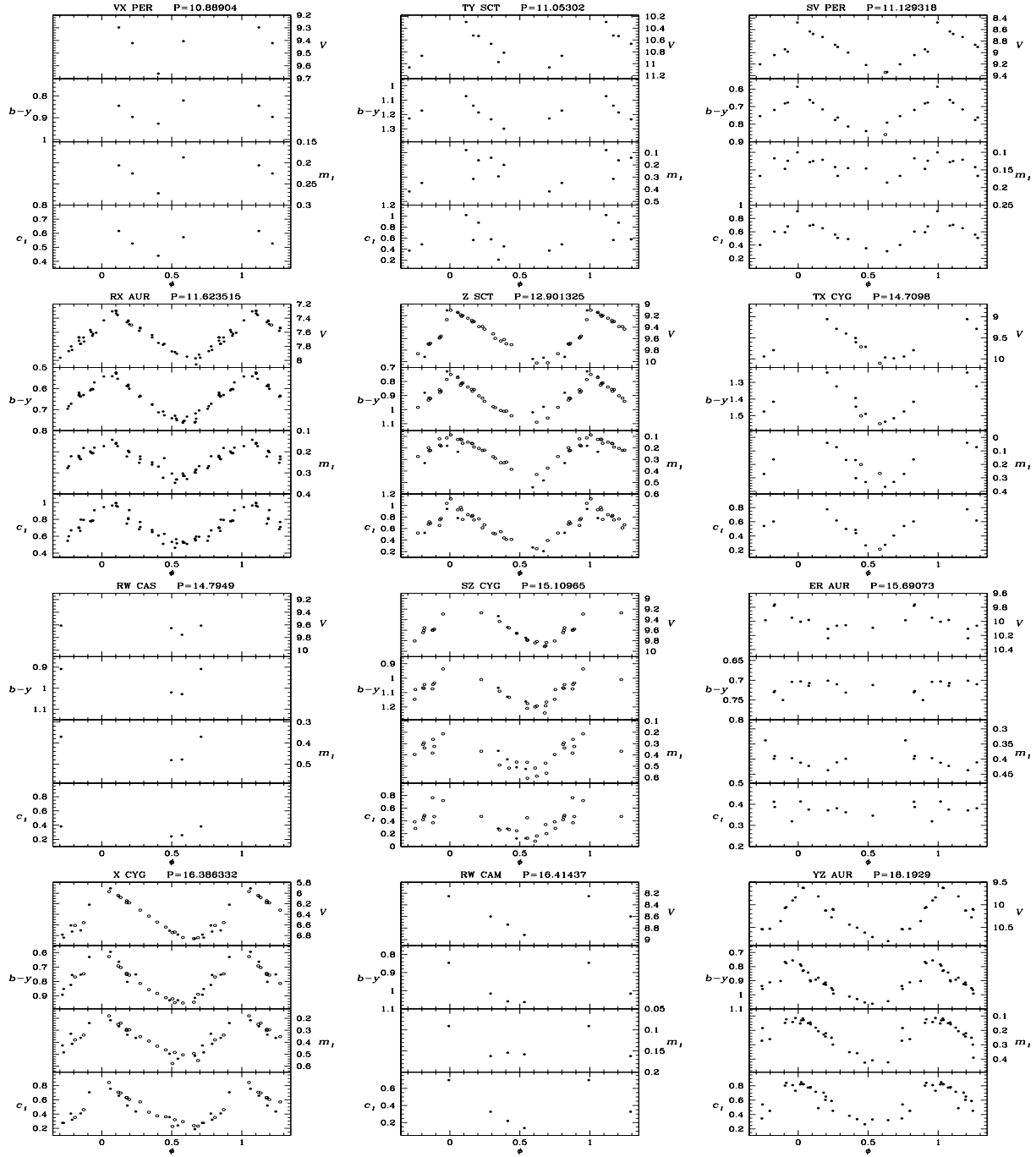


Fig. 5. continue



TABLE 4  
OBSERVED STARS IN  $uvby - \beta$

Star	Epoch	Period	AF <sup>1</sup> 1998	Eggen 1983	Meakes 1991	F&McN <sup>2</sup> 1980	This paper
SW TAU	41687.77	1.583584	6		7		5
EU TAU	41324.22	2.10248					14
SZ TAU	34628.57	3.14873	6			28	46
SS SCT	35315.625	3.671253	26	13		29	0
RT AUR	42361.155	3.728115					11
Y AUR	37203.629	3.859485	1				37
CM SCT	35111.32	3.916977					21
ST TAU	41761.963	4.034299	2				42
X SCT	34905.58	4.19807					16
VZ CYG	41705.702	4.864453	9			30	10
AS PER	41723.934	4.972516					13
BG LAC	35315.273	5.331908				26	18
UY PER	44945.845	5.365106					3
BX SCT	27901.83	6.41133					11
AW PER	42709.059	6.463589				23	11
AO AUR	42815.86	6.763006					15
CK SCT	40855.25	7.41522					13
RS ORI	42820.794	7.566881	10	21			25
VY CYG	43045.282	7.856982	2				10
RX CAM	42766.583	7.912024					4
BK AUR	17377.719	8.002432					16
CN SCT	28670.16	9.9923					7
SY AUR	36843.52	10.144698	1				36
AN AUR	36843.309	10.29056					46
Y SCT	34947.2	10.341504	27				5
Z LAC	42827.123	10.885613	5			25	15
VX PER	43758.994	10.88904					4
TY SCT	37377.09	11.05302					8
SV PER	43839.296	11.129318	1				14
RX AUR	39075.63	11.623515				21	61
Z Sct	36247.16	12.90133	27				5
TX CYG	43794.971	14.7098					10
RW CAS	35575.227	14.7949					3
SZ CYG	43306.79	15.10965	10				5
ER AUR	43861.3	15.69073					11
X CYG	43830.387	16.386332	18			53	13
RW CAM	37389.57	16.41437					4
YZ AUR	37431.141	18.193212					28
RU SCT	31174.67	19.70062	27				8
VX CYG	43783.642	20.133407	6				13

<sup>1</sup>Arellano Ferro et al. (1998)<sup>2</sup>Feltz & McNamara (1980)

TABLE 5  
SAMPLE OF  $uvby - \beta$  OBSERVATIONS OF CLASSICAL CEPHEIDS

Star	$V$	$b - y$	$m_1$	$c_1$	HJD( $uvby$ )	$\beta$	HJD( $\beta$ )	$P(days)$
SW TAU	9.694	0.443	0.152	0.982	2447833.9053	2.713	41687.77	1.583584
SW TAU	9.712	0.410	0.112	1.076	2447837.9903	2.729	41687.77	1.583584
SW TAU	9.916	0.522	0.152	0.826	2454190.6381		41687.77	1.583584
SW TAU	9.366	0.364	0.100	1.269	2454191.6274		41687.77	1.583584
SW TAU		0.514	0.148	0.809	2454192.6355		41687.77	1.583584